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Interstellar medium of Galaxy in the optical range

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Abstract. The paper briefly presents the results of spectral studies of interstellar medium in the wavelength range from near-ultraviolet to near IR. Particular attention is paid to the mysterious diffuse interstellar bands (DIBs), which have remained unidentified since 1922. The connection between different components of the interstellar medium and possible candidates for the carriers of diffuse bands are discussed.

Keywords: ISM: clouds; diffuse interstellar bands

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1 Interstellar atoms/ions

More than 150 years have passed since it was proposed that interstellar medium, an absorbing medium of dust and gas (Struve 1847), fills the space between the stars. In the early 20th century Hartmann (1904) demonstrated the first observational evidence for absorption occurring in the interstellar medium, which manifested itself in the form of stationary absorptions (H and K lines of Ca II) observed in the spectra of the binary star δ Orionis.

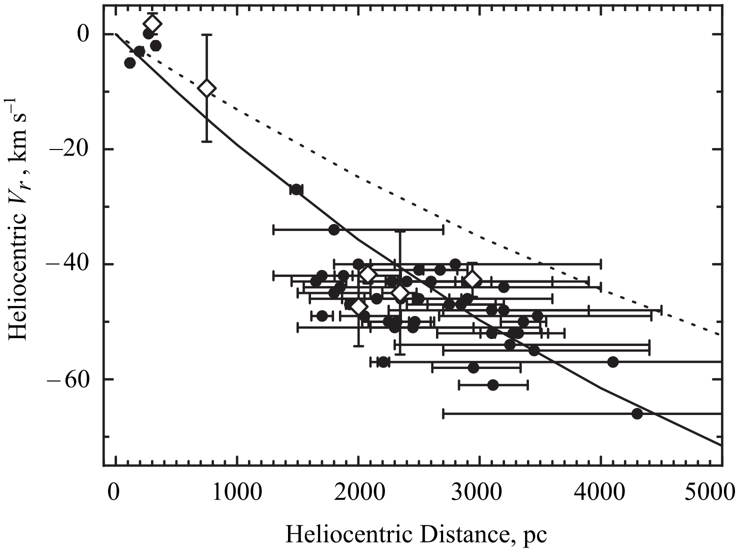

Fig. 1. Radial velocity curve for the direction $l = 135°$. "Flat" rotation (dotted line) and Keplerian (solid line) theoretical curves are shown. Filled circles represent our observed objects (Ca II clouds) and open diamonds represent literature data for open clusters. See Galazutdinov et al. (2015) for details.

Further studies have shown the complex structure of the interstellar medium, for example Beals (1936) discovered double and asymmetric components of the H and K lines visible in the spectra of stars in the constellation Orion. Spectral lines of ionized calcium (H and K) and neutral sodium (D_2 and D_1) are the strongest interstellar lines in the optical range, visible even in the spectra of stars with reddening close to zero. The list of interstellar atomic lines observed in the optical range is relatively short. In addition to the already mentioned strong lines with the wavelengths of 3933.663, 3968.468, 5889.951, 5895.924 Å respectively, one can also see strong lines of the neutral potassium doublet at 7664.994 Å and 7698.965 Å. However, the 7664.994 Å line is almost always blended with strong telluric lines and cannot be precisely measured. The remaining interstellar atomic lines visible in optical range are very weak even in a case of significant interstellar reddening. Most of them are in the near ultraviolet, but several lines are also observed in the visible range. There are, for example, the lines of Fe I $\lambda3440.607$, $\lambda3719.935$, $\lambda3859.911$; Ti II $\lambda3073$, $\lambda3229.19$, $\lambda3241.983$; in contrast to the D doublet, the ultraviolet sodium doublet 3302 Å is much less affected by the saturation effect; forbidden lines of neutral helium He I* $\lambda3888.63$ and $\lambda10\,830.3$, observed only in the direction of very hot stars; a relatively strong line of neutral calcium 4226.728 Å, usually observed even with moderate interstellar reddening; very weak lines of interstellar lithium 6708 Å; finally, a weak line of interstellar rubidium Rb I $\lambda7800.27$. Due to the extremely low density and low temperature typical for H I clouds, interstellar absorptions in the optical spectra are very narrow, i.e. high resolving power is required to study their profiles—at least ($R > 80\,000$) is necessary. With higher spectral resolution and S/N ratio, an increasing number of components are observed in the spectral line profiles. For example, the profiles of interstellar lines of Na I, Ca II, K I, CH, CH+ demonstrate that even ultra-high $R \sim 900\,000$ may be insufficient to separate all individual profile components (Price et al. 2001).

One of most interesting results, based on the analysis of interstellar atomic absorptions, namely, lines of Ca II was obtained by Galazutdinov et al. (2015). Authors demonstrated that the rotation curve of the Galaxy is generally thought to be flat. However, using radial velocities from interstellar molecular clouds, which is common in rotation curve determination, seems to be incorrect and may lead to erroneous conclusion that the rotation curve is flat indeed (Galazutdinov et al. 2015). Tests based on photometric and spectral observations of bright stars may be misleading as well. The rotation tracers (OB stars) are affected by motions around local gravity centers and pulsation effects seen in such early type objects. To get rid of the latter a lot of observing work must be involved. We introduced a method of studying the kinematics of the thin disc of our Galaxy outside the solar orbit in a way that avoids these problems. We proposed a test based on observations of interstellar Ca II H and K lines that determines both radial velocities and distances. We implemented the test using stellar spectra of thin disk stars at galactic longitudes of 135° and 180°. Using this method, we constructed the rotation curve of the thin disk of the Galaxy. The test leads to the obvious conclusion that the rotation curve of the thin gaseous galactic disk, represented by the Ca II lines, is Keplerian outside the solar orbit rather than flat (Fig. 1).

2 Interstellar molecules

The first interstellar molecules (CH, CN, CH+) were discovered in the optical spectra of nearby stars (Dunham 1937; McKellar 1940; Adams 1941; Douglas & Herzberg 1941). Just 30 years later some more complex interstellar molecules were discovered (e.g., NH_3, Cheung et al. 1968). Currently, more than 310 molecules have been discovered in the interstellar and circumstellar medium of the Galaxy. Some 74 molecules have been discovered outside the Galaxy (including three unconfirmed candidates). Molecules are mainly discovered in the radio and submillimeter spectral regions at a rate of several “new” molecules per year. Only about ten simple molecules are observed in the visible part of the electromagnetic spectrum as absorption lines arising in translucent clouds. Among them are homonuclear molecules such as H_2, C_2, C_3, which are inaccessible to radio telescopes. In simple carbon chains (without radicals) there are no pure rotational transitions due to the absence of a permanent dipole moment. Electron-vibrational transitions of such molecules are observed in the wavelength range from the ultraviolet, accessible only for extra-atmospheric observations, to the far infrared range, i.e. they are accessible for observations by optical spectrographs. Determination of the abundance of simple carbon molecules in interstellar clouds is especially important, since they are considered to be the building blocks for many already known interstellar molecules with a carbon base. Douglas (1977) argued that carbon chains may be responsible for the formation of diffuse interstellar bands. Unfortunately, molecular lines observed in the optical range usually are very weak, necessitating high spectral resolution spectra with very high signal-to-noise ratio. Such spectra allows to detect extremely weak features of new molecules or never before observed bands of known molecules as it was done by us in Schmidt et al. (2014), Zhao et al. (2015a,b).

3 Diffuse interstellar bands

According to current knowledge, the composition of the interstellar absorbing matter is very complex: for example, molecules consisting of dozens of atoms have already been detected. Another, perhaps the most striking evidence of complex molecular synthesis/destruction processes occurring in the interstellar medium is the existence of diffuse interstellar bands (DIBs), the oldest unsolved problem in astronomical spectroscopy. DIBs were discovered in 1922 (Heger 1922), but their carriers remain unknown, (with perhaps one exception, see below) despite significant efforts by astronomers and progress in observational astronomy over the past 30 years. The list of discovered DIBs continues to grow, including increasingly weaker lines. The current list of DIBs includes more than 500 items(Galazutdinov et al. 2000, 2017; Fan et al.

2019). For reviews of the properties of DIBs, see, for example, Herbig (1995), Sarre (2006), Krełowski (2018).

The rest wavelengths of DIBs are the parameters of fundamental importance owing to the lack of unambiguous identification for these mysterious features. Recently (Galazutdinov & Babina 2024) we proposed the narrowest known diffuse interstellar band 6196 Å as the best reference for building the "interstellar" wavelength scale. Then, we estimated the magnitude of variation of the gravity center (the effective wavelength) of diffuse bands at 5780, 5797, 6284 Å and 7224 Å measured in 41 lines of sight in the range of interstellar reddening of 0.13–1.06 stellar magnitudes with the lack of evident Doppler-split in profiles of interstellar atomic/molecular lines. DIBs show gradual broadening of their profile widths, accompanied with red-shift of the gravity center, i.e. the red wing of the profiles is most variable part of the profiles. We offered to apply a parameter "effective width" W_{eff}, which is a ratio of the equivalent width to the depth of the feature. In contrast to habitual full width at half maximum (FWHM) W_{eff} is not sensitive to the profile shape irregularities and can be measured in noisy spectra with higher precision than it is for FWHM. The gradual increase of W_{eff}, accompanied with the red-shift of the gravity center of the profile, may suggest populating of higher transitions of P-branch of the bands of molecules, assuming the latter are DIB carriers. DIBs are broader but shallower in the harsh conditions of σ-clouds, where atomic and molecular lines are weak/absent.

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